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Water resources for agriculture in a changing climate: international case studies

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Abstract

This integrated study examines the implications of changes in crop water demand and water availability for the reliability of irrigation, taking into account changes in competing municipal and industrial demands, and explores the effectiveness of adaptation options in maintaining reliability. It reports on methods of linking climate change scenarios with hydrologic, agricultural, and planning models to study water availability for agriculture under changing climate conditions, to estimate changes in ecosystem services, and to evaluate adaptation strategies for the water resources and agriculture sectors. The models are applied to major agricultural regions in Argentina, Brazil, China, Hungary, Romania, and the US, using projections of climate change, agricultural production, population, technology, and GDP growth.

For most of the relatively water-rich areas studied, there appears to be sufficient water for agriculture given the climate change scenarios tested. Northeastern China suffers from the greatest lack of water availability for agriculture and ecosystem services both in the present and in the climate change projections. Projected runoff in the Danube Basin does not change substantially, although climate change causes shifts in environmental stresses within the region. Northern Argentina's occasional problems in water supply for agriculture under the current climate may be exacerbated and may require investments to relieve future tributary stress. In Southeastern Brazil, future water supply for agriculture appears to be plentiful. Water supply in most of the US Cornbelt is projected to increase in most climate change scenarios, but there is concern for tractability in the spring and water-logging in the summer.

Adaptation tests imply that only the Brazil case study area can readily accommodate an expansion of irrigated land under climate change, while the other three areas would suffer decreases in system reliability if irrigation areas were to be expanded. Cultivars are available for agricultural adaptation to the projected changes, but their demand for water may be higher than currently adapted varieties. Thus, even in these relatively water-rich areas, changes in water demand due to climate change effects on agriculture and increased demand from urban growth will require timely improvements in crop cultivars, irrigation and drainage technology, and water management.
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Keywords: Climate; Climate change; Water supply; Water demand; Agriculture; Irrigation; Adaptation

1. Introduction

Climate change, population growth, and economic development will likely affect the future availability of water resources for agriculture differently in different regions. The demand for and the supply of water for

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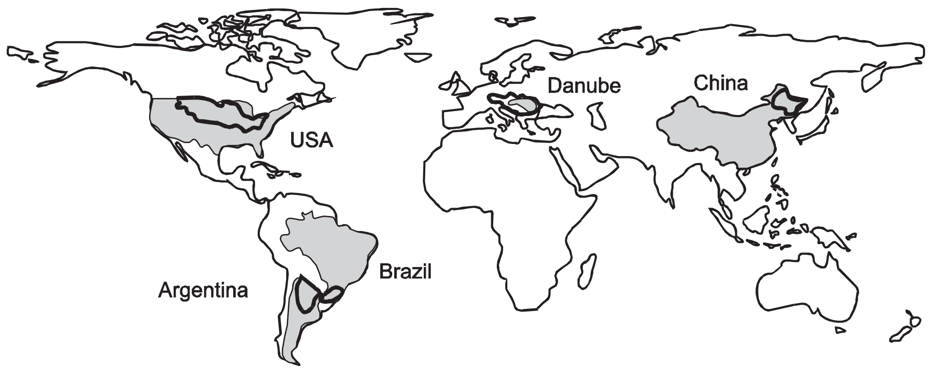

Fig. 1. Study countries and regions.

irrigation will be influenced not only by changing hydrological regimes (through changes in precipitation, potential and actual evaporation, and runoff at the watershed and river basin scales), but by concomitant increases in future competition for water with non-agricultural users due to population and economic growth. Here we compare future water availability for agriculture and its ability to provide ecosystem services under changing climate conditions in case study regions throughout the world. The study regions are in Northern Argentina, Southeastern Brazil, Northeastern China, the Hungarian and Romanian parts of the Danube Basin, and the US Cornbelt (Fig. 1). (Results from the US Cornbelt case study are discussed in detail in Strzepek et al., 1999.) We evaluate near-term adaptation strategies for both the water resources and agricultural sectors in the regions.

The regions differ in socio-economic development, technological possibilities, and climatic regime, but all have relatively ample (less in Northeastern China) water supplies for agriculture in the current climate. Thus, one purpose of the study is to consider how major agricultural regions may fare under changing climate conditions, since they may become even more important as food-producing centers relative to agricultural areas in more marginal, semi-arid regions that have been found to be vulnerable to climate change (IPCC, 2001a). The objective here is to develop a comparative framework for regional water resources for agriculture that integrates water availability, agriculture, and technology with demographic, economic, and climate forecasts.

The framework was developed by an interdisciplinary team and uses publicly available and widely validated models of water supply and demand and of crop growth and irrigation management. The models are validated at both site and regional scales, permitting the evaluation of uncertainties at different spatial scales. Consistent modeling assumptions, available databases, and scenario simulations are applied to major agricultural regions, capturing a range of possible future conditions. We tested the sensitivity of the modeling framework to technological change and also observed the degree of environmental stress in each basin under alternative scenarios. For two of the case studies, those in China and the US, we examined additional forecasts and the use of different cultivars (varieties) for adaptation to changing seasonality. Among earlier uses of integrated model methodology are Strzepek et al. (1999); Strzepek et al. (1995); Rosenzweig and Parry (1994); and Major and Schwarz (1990).

The agricultural regions chosen for the comparative study include major corn and soybean growing areas and associated river basins (Table 1). The selection of these areas is based on their importance in current or potential corn and soybean production, and on their sensitivity to current and future climate regimes (see e.g., Lobell and Asner, 2003). The countries within which the study areas are located contain about one-third of global arable land and irrigated land, and currently account for about 70% of world corn production and over 90% of world soybean production (FAO, 1998).

The methods are an improvement over other approaches in several respects. Potential evapotranspiration is calculated consistently for both the supply of and the demand for crop irrigation water in the agricultural regions of each water basin. A weather generator is used to develop monthly time series for the climate change scenarios with spatial autocorrelation that permits analysis of potential changes in interannual variability. Trajectories of change in competing demands for water and demand for agricultural commodities based on population growth and economic development, and improvements in irrigation technology are included, as well as potential changes in climate. The use of water for ecosystem services is considered explicitly. The importance of using several forecasts of climate change in analyses is bolstered by considering the work of Stone et al. (2001), whose single forecast (albeit converted to mesoscale, a computationally intensive procedure), does not provide water managers with a range of possibilities for the same region considered in Strzepek et al. (1999). Finally, adaptation

Table 1
Description of study areas

Case study	Area (km^2)	Rivers	Water regions	Administrative units
Argentina	830,700	Parana (part)	4	Chaco, Cordoba, Santa Fe, Santiago del Estero[a]
Brazil	329,741	Uruguay and tributaries (part) coastal rivers	5	Rio Grande do Sul Santa Catarina
China	642,000	Songhua Jiang Di'er Songhua Nen Jiang	3	Jilin, Heilongjiang, Inner Mongolia Autonomous Region
Hungary and Romania	851,280	Lower Danube	7	Hungary: 20 counties Romania: 42 counties Bordering countries[b]
United States	2,281,917	Upper/Middle/Lower Missouri Upper/Middle Mississippi Ohio	6	All or part of 21 states[c]

[a]And parts of Catamarca, Formosa, Jujuy, Salta, and Tucuman.
[b]Parts of water regions located in Austria, Bosnia-Herzogovina, Bulgaria, Croatia, Czech Republic, Germany, Macedonia, Moldavia, Slovakia, Slovenia, Ukraine, Yugoslavia.
[c]All or parts of Colorado, Illinois, Indiana, Iowa, Kansas, Kentucky, Maryland, Minnesota, Missouri, Montana, North Carolina, New York, North Dakota, Ohio, Pennsylvania, South Dakota, Tennessee, Virginia, West Virginia, Wisconsin, Wyoming.

measures are evaluated from the point of view of both water resource and agronomic management.

2. Methods

The modeling structure of the study is shown in Fig. 2, which illustrates the linkages of the water supply, crop demand, and water management models. The linked models include WATBAL for water supply (Yates, 1996; Kaczmarek, 1993); CERES-Maize, SOYGRO, and CROPWAT for crop yield and irrigation demand (Jones and Kiniry, 1986; Jones et al., 1988; CROPWAT, 1995); and WEAP for water demand forecasting, planning and evaluation (Stockholm Environment Institute, 1997; Sieber et al., 2002). These models are applied to the study regions for current conditions and for a set of scenarios projecting future changes in climate, agricultural production, population and GDP. For further information about models and methods, see http://www.giss.nasa.gov/research/impacts.

2.1. Study regions

Major maize and soybean growing areas and associated river basins in Hungary and Romania, Argentina and Brazil, China, and the United States were selected as case studies (see Fig. 1 and Table 1). The boundaries of the study areas were defined by the location of major river basins and agricultural production areas. Each case study was subdivided into smaller water regions, generally comprising a single river with its tributaries, but sometimes including additional streams. The major maize and soybean growing areas, crop modeling sites,

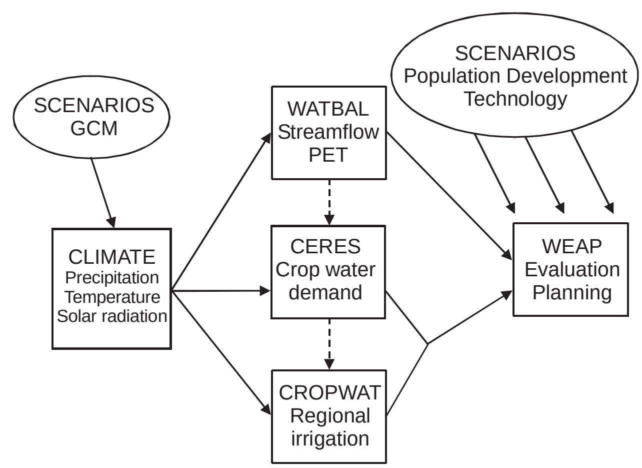

Fig. 2. Model structure and interactions.

and associated water regions for each study area are shown in Fig. 3.

2.2. Climate change scenarios

The system of models is driven by climate change scenarios that represent a range of plausible future climate changes as projected by global climate model (GCM) simulations available at the initiation of the interdisciplinary study. The GCMs are those of the Geophysical Fluid Dynamics Laboratory (GFDL) (R30 version) (Manabe et al., 1992), Goddard Institute for Space Studies (GISS) (Hansen et al., 1984), and the Max Planck Institute (MPI) (Cubasch et al., 1992), with sensitivities to doubled CO_2 forcing of 3.7 °C, 4.2 °C, and 2.6 °C, respectively. In order to compare results from the original set of GCMs with more recent ones,

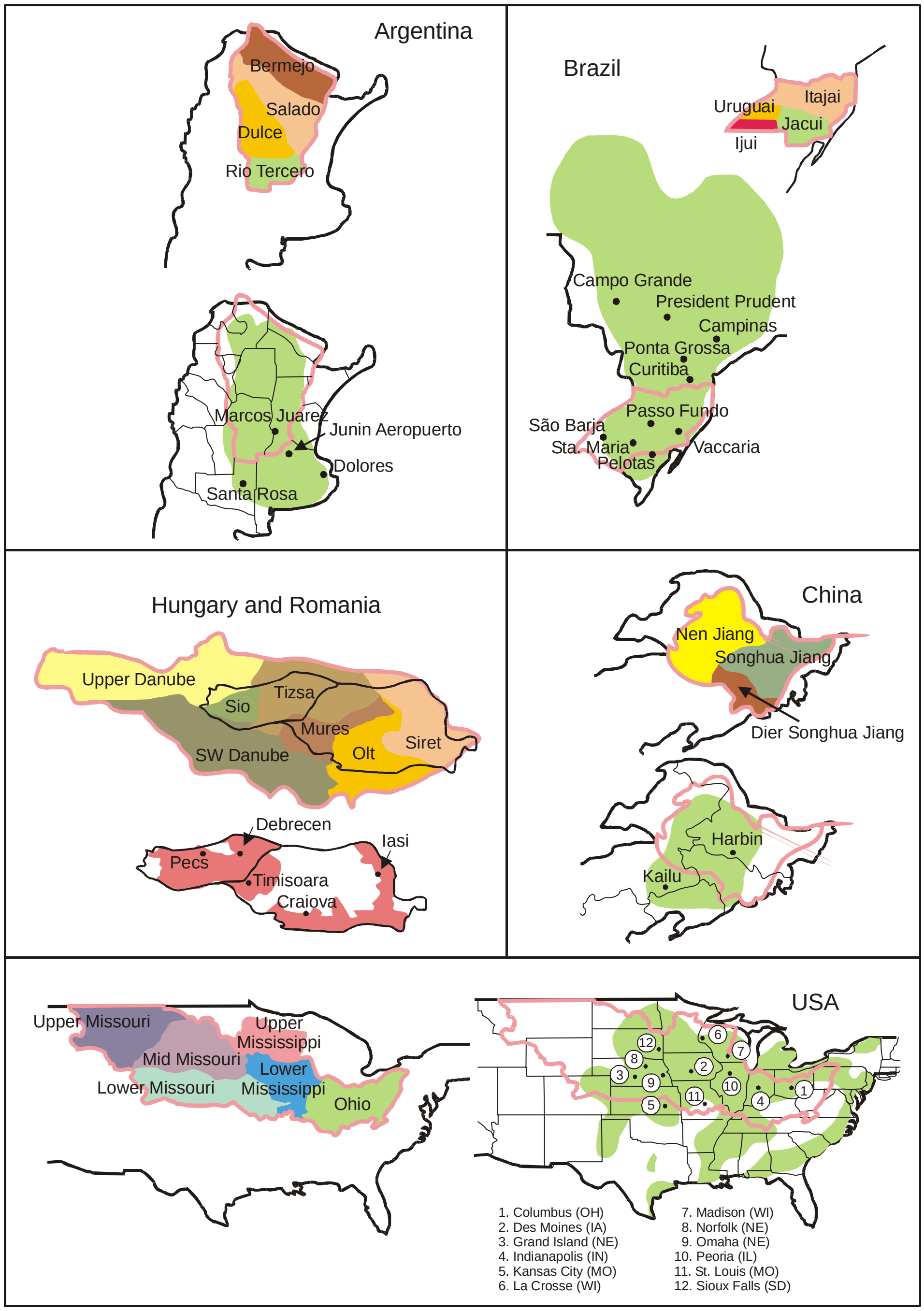

Fig. 3. Study areas, water regions, and crop modeling sites for Argentina, Brazil, China, Hungary and Romania, and the United States.

we also used two additional GCMs: those of the United Kingdom Met Office Hadley Centre (HadCM2) (HC) (Mitchell et al., 1995; Johns et al., 1997) and the Canadian Climate Centre (CGCM2) (CCC) (Flato and Boer, 2001). These GCM transient simulations were forced with a 1% per year increase of CO_2 concentrations, which represents a mid-range of non-intervention CO_2 emissions trajectories available from surveyed literature (Nakicenovic and Swart, 2000).

Time periods for the analysis reflect key periods relevant to water resource management decision-makers: near-term (the 2020s) and medium-term (the 2050s). The climate change scenarios for the 2020s and the 2050s are constructed from the 30-year period centered on the given time-slice. The GCM scenarios selected did not include the effect of sulfate aerosols; temperature projected for combined greenhouse gas and sulfate aerosol effects would be slightly reduced. The projections used fall within the range of forecasts reported in the 2001 IPCC Third Assessment Report (IPCC, 2001b).

Monthly mean temperature, precipitation and solar radiation changes are obtained for the study regions and are used to create climate change scenarios for the water supply and crop models. For the crop modeling sites, daily climate data are modified by monthly changes taken from the GCMs. For the water supply modeling, the monthly changes are applied to the monthly Stochastic Analysis and Modeling System (SAMS) time-series (United States Bureau of Reclamation, 1999). The SAMS model provides a stochastic, spatially explicit technique for generating regional weather time series preserving auto- and cross-correlations.

2.3. Modeling water supply

Water supply is calculated with WATBAL, a model developed for the evaluation of climate change impacts on river basin runoff (Kaczmarek, 1993; Yates, 1996). The model calculates the monthly water balance of a water region as a single hydrologic entity with quantifiable water inflows, outflows, and usable supplies. For this study, WATBAL was modified to use the Priestley-Taylor (1972) method for computing potential evapotranspiration (ET0) as specified by Ritchie (1972), insuring consistency with the crop and irrigation management models at the site and regional scales (Fig. 4). WATBAL has been widely validated for use in

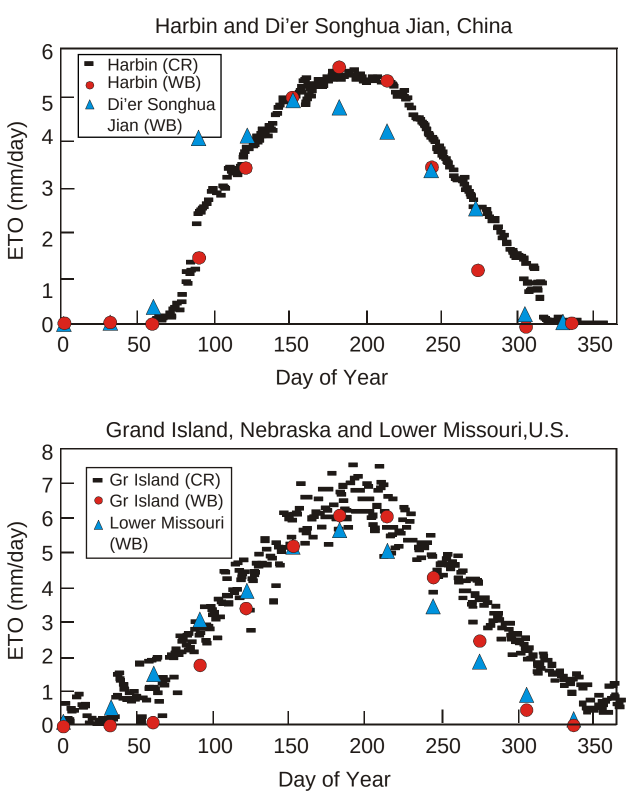

Fig. 4. Potential evapotranspiration (ET0) calculated with the DSSAT agricultural models with observed precipitation data at the daily time step (CR) and the WATBAL hydrological model with simulated gridded precipitation data at the monthly time step (WB) at the site (- and ●), and water region (▲) scales in China and US.

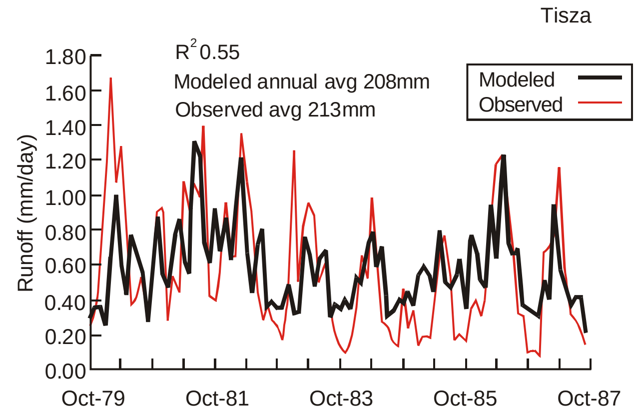

Fig. 5. Observed and modeled monthly runoff for the Tisza water region in the Danube basin.

climate change studies (Strzepek et al., 1999; Yates, 1996; Strzepek et al., 1995); a comparison to observed runoff for river basins in the Danube Basin is shown in Fig. 5. For each region, WATBAL is run with a 50-year time-series for the current climate and for each of the climate change scenarios, using SAMS. Inputs are monthly precipitation and temperature. Continuous functions of relative storage in the form of differential equations represent surface outflow, sub-surface outflow, and evapotranspiration.

2.4. Modeling water demands for agriculture

Crop water demands for corn and soybean are estimated with CERES-Maize and SOYGRO, dynamic process crop growth models, and CROPWAT, an irrigation management model. CERES-Maize (Jones and Kiniry, 1986) and SOYGRO (Jones et al., 1988) describe daily phenological development and growth in response to environmental factors (soils, weather and management). They utilize the Priestley-Taylor (1972) method of estimating potential evapotranspiration, and have been calibrated and validated over a wide range of agro-climatic regions (Rosenzweig and Iglesias, 1994). The direct physiological effects of carbon dioxide on crop growth and water use are taken into account, as described by Peart et al. (1989) and Rosenzweig and Iglesias (1994). The crop models are embedded in the Decision Support System for Agrotechnology Transfer (DSSAT) (IBSNAT, 1989), a software package that includes crop models and routines for analyzing climate inputs, model results, and management strategies.

The crop models were run at each of the sites in Figure 3 for current and changed climates; simulations were done for both rainfed and fully irrigated production under conditions of adequate nitrogen fertilization. Time series of daily climate data (maximum and minimum temperature, and precipitation) were obtained from Dr. Roy Jenne of the National Center for

Atmospheric Research (NCAR). Daily solar radiation was estimated using the WGEN weather generator (Richardson and Wright, 1984). Soils at all sites were designated as medium silt loam 90 cm deep, representing moderately productive agricultural capability. Crop cultivars and management inputs were specified to represent current practices (Rosenzweig and Iglesias, 1994). In the climate change simulations, planting dates were adjusted to account for autonomous farmer adaptation to changing climate conditions.

The ratio (K_c) between actual crop evapotranspiration and potential evapotranspiration is calculated from the CERES and SOYGRO model simulations for the current climate and for the climate change scenarios for each site. K_c, monthly precipitation from SAMS, and monthly potential evapotranspiration calculated from WATBAL (the latter two representing the supply and atmospheric demand for water at the regional scale) are then used as inputs to CROPWAT to estimate regional demand for irrigation. CROPWAT is an empirical irrigation management model developed by the United Nations Food and Agriculture Organization (FAO) to calculate regional crop water and irrigation requirements from climatic and crop data (CROPWAT, 1995). Irrigated cropping areas for use in CROPWAT for corn, soybean, and other crop areas were estimated from FAO (1998) and National Agricultural Statistical Service (USDA, 1999). Net irrigation demand (balance between crop evapotranspiration and water available for the crop) for each region was calculated. Demands were adjusted by an estimated irrigation efficiency for use in the WEAP model.

2.5. Water evaluation and planning model (WEAP)

Assessment of the balance of water supply and demand for the study regions is undertaken in the water evaluation and planning (WEAP) model (Sieber et al., 2002; Stockholm Environment Institute, 1997; US Army Corps of Engineers, 1994). The WEAP model is an integrated decision support system (DSS) designed to support water planning that balances water supplies generated through watershed-scale physical hydrologic processes and multiple water demands and environmental requirements characterized by spatially and temporally variable allocation priorities and supply preferences (Sieber et al., 2002). The model allows for the specification of the water system in each water unit. WEAP employs a priority-based optimization algorithm, as an alternative to hierarchical rule-based logic that uses a concept of equity groups to allocate water in times of insufficient supply. WEAP was developed by the Stockholm Environment Institute's Boston Center at the Tellus Institute (http://www.weap21.org/).

The WEAP model integrates the changes in water supply projected by the WATBAL model and the changes in crop water demands projected by CERES-Maize, SOYGRO and CROPWAT with population, economic, and technological forecasts. In this study, municipal and industrial uses are given priority over agriculture, and demands are met based on a rule that draws first from river flow and then from available storage. WEAP inputs and demands are specified for a base year of 1995. Data are taken from 1995 where available, are extended to that year, or are taken from other years when they approximate 1995 values. As in the WATBAL model, the water supply in each water region in the WEAP model is conceived as a single unit representing available flow. Sustainable water supply is taken as the joint surface and groundwater yield of a basin. This neglects, for example, the groundwater used in irrigation that is abstracted from "tributary" aquifers, which would end up as stream-flow or surface water with a time lag. Other irrigation supplies from surface water are not included in the model structure (Strzepek et al., 1999). The WEAP model is specified at too coarse a spatial scale to simulate ground and surface water in detail, but divided into individual water regions, as here, is useful as a regional planning tool. Regional water supply is derived from the multi-year results of the WATBAL simulations.

2.6. Demographic and economic drivers

To project water supply and demand into the future, variables relating to technology, population, and development are specified, as well as assumptions about institutions. Population and GDP drivers are used to calculate future industrial, municipal, and domestic water use, and to forecast increases in irrigation area (see Strzepek et al., 1999). For population projections, we use low and high variants of population forecasts at the national level (United Nations, 1996) with a base year of 1995 and a furthest forecast year of 2050. Forecasts of world and regional economies are based primarily on the Netherlands Central Planning Bureau (1992) study, extended to the 2050s.

Forecasts of industrial water use in the model are driven by growth in forecast GDP, while forecasts of municipal and domestic water use in the model depend on population growth. We project the expansion of irrigated area in the case study regions according to growth rate estimates for world population and world GDP (representing per capita income).

2.7. Scenario design and model analyses

The goal is to contrast the future without climate change with a range of possible futures with climate change taken into account. A relatively *Optimistic Future*, with lower population growth rates, higher economic development rates and more efficient water-use technology, is contrasted with a more *Pessimistic Future*, with higher population growth rates, slower economic development and less efficient water-use technology. The optimistic future corresponds, at least in part, to the IPCC SRES A1 scenario with lower population growth, higher GDP growth rates, and rapid introduction of new and more efficient technologies, while the pessimistic future corresponds roughly to the A2 scenario with higher population growth, lower GDP growth, and fragmented and slower technological change (Nakicenovic and Swart, 2000). Three climate change scenarios are imposed on each of the futures to capture a range of potential changes in temperature and precipitation projected by global climate models. Additional modeling analyses were undertaken in regard to ecosystem services, assumptions of technological improvement, seasonality of supply and demand balance, possible surprises, and potential changes in climate variability.

2.8. Agronomic adaptation

Annual and seasonal climate changes imply the need for adaptations; these can include changes in planting schedules, and adaptations of crop genetic characteristics such as maturity class, heat tolerance, vulnerability to pests, and sensitivity to pesticides. The objective here is to develop quantitative and qualitative guidelines for cultivar adaptations to projections of altered seasonality under climate change regarding duration of growth stages and photoperiod sensitivity. A detailed assessment was conducted of crop growth parameters in DSSAT under seasonality changes derived from the GCM climate change scenarios using alternative maize cultivars and crop planting dates.

The selected set of maize cultivars represents a wide range in terms of productivity and phenology for different agro-climatic zones. Other cultivars may be different in terms of resistance to pests or pesticides, but the simulations did not include those characteristics. The tested cultivars are not currently used in the US Corn Belt and represent an initial test of possible changes of cultivars under climate change conditions. Alternatives for soybean were not tested, because the effects of climate on output for soybean are less significant for the climate change scenarios selected for the study. In general, soybeans are less negatively affected by the small increases in projected temperature, which are generally within the range of the current temperatures of the US Corn Belt.

2.9. Caveats

Global climate models are still not capable of simulating current regional hydrologic regimes to desirable levels of accuracy; hence we utilize their results only as suggestive of regional vulnerability to the range of projected changes rather than as absolute predictions. Interbasin transfers are not explicitly modeled, and the institutional and decision-making structures included in the model system are generalized. The economic and demographic forecasts are not completely consistent. For example, the assessments of alternative economic futures used in the simulations employ somewhat different population assumptions than the UN projections. Despite these caveats, the integrated modeling framework does provide useful results for considering water resource and agronomic management under changing future conditions in the case studies.

3. Results and discussion

We discuss projected changes in water supply, crop water demand, and the integrated supply and demand balance for the case study regions from the WEAP model. The projections of water availability are presented for the optimistic and pessimistic core set of simulations with the three climate change scenarios. We then present comparative analyses in regard to technological improvement and potential for agronomic adaptation.

3.1. Detecting climate change

An important factor for regional water managers in planning for adaptation is to gain perspective on when climate changes might rise above the 'noise' of current climate variability (see, e.g., Hulme et al., 1999). To begin to address this, we compared projected change in annual precipitation for the 2020s and 2050s to the standard deviation of precipitation in the base climate for selected basins and study regions. Table 2 shows that projected changes for the GFDL and GISS scenarios mostly do not exceed current climate variability, while projected changes for the MPI scenario exceed current variability in several basins. The relatively small projected precipitation changes should be borne in mind in evaluating the following analyses. However, precipitation is not the only factor that affects water supply and demand; one needs to consider concurrent projected changes in temperature, potential evaporation, snow, and runoff as well. A further interesting point to note is that precipitation changes projected for the 2050s often change sign from those projected for the 2020s.

3.2. Changes in water supply

Table 3 shows the impacts of the GCM climate change scenarios on total runoff in the study regions for the 2020s as calculated by WATBAL. For all regions,

Table 2
Change in annual precipitation for selected water regions in the GFDL, GISS, MPI, CCC, and HC climate change scenarios for the 2020s and 2050s compared to standard deviation of base climate precipitation

Country/water region	Base annual precipitation (mm)		Scenario changes in annual precipitation 2020s (mm)					Scenario changes in annual precipitation 2050s (mm)				
	Avg	StdDev	GFDL	GISS	MPI	CCC	HC	GFDL	GISS	MPI	CCC	HC
Argentina and Brazil												
Rio Tercero	834	168	98	37	80			23	103	27		
Itajai	1623	288	390[a]	−244	61			140	56	−42		
China												
Nen Jian	424	104	−4	24	100	−81	26	0	23	110	−76[a]	15
Di'er Songhua Jiang	842	136	16	29	180[a]	−154[a]	71	20	7	63	−115	35
Hungary and Romania												
Siret	579	139	89	28	377[a]			39	81	512[a]		
Tisza	604	128	22	16	130			19	54	307[a]		
United States												
Upper Missouri	352	83	44	22	−32	27	23	51	44	−31	−94[a]	17
Lower Missouri	652	148	54	26	−192[a]	170	57	51	53	−131	−249[a]	25
Upper Mississippi	693	142	132	69	−144[a]	235[a]	51	103	67	−155[a]	−37	47

[a]Change greater than standard deviation in current climate.

Table 3
WATBAL regional water supply (runoff) for base climate and the 2020s

	2020s Scenario runoff (10^9 m^3)			
Country	Base	GFDL	GISS	MPI
Argentina	121	109	129	110
Brazil	239	337	230	249
China	67	59	74	73
Hungary and Romania	302	307	313	459
US	462	525	465	369

Note: Base climate = 50 years of SAMS data for each water region (USBR).

the GCMS project changes in runoff that vary in sign and magnitude, indicating that global climate change presents uncertainties in regard to water supplies in the future. Model-predicted changes in runoff are small in Argentina, China and Hungary and Romania, while larger changes are found in Brazil and the US. The US shows potential for large increases in two of the three scenarios.

Overall, increases in runoff tend to predominate in the results. While there is variation among the 27 water regions across the five case study areas, the results of the GCM scenarios suggest that excess water could be a more damaging aspect of climate change than drought in some locations (Rosenzweig et al., 2002). Climate change can also alter the timing of water supply on seasonal timescales (Gleick and Chalecki, 1999), a point illustrated by detailed simulations relevant to potential temporal changes in the Lower Missouri water region (Strzepek et al., 1999).

Table 4
Projected change in irrigation water demand

Country—water region	2020s Scenario irrigation demand (%)			2050s Scenario irrigation demand (%)		
	GFDL	GISS	MPI	GFDL	GISS	MPI
Argentina						
Rio Tercero	45	38	18	65	61	74
Dulce	38	18	0	51	31	46
Salado	42	13	−2	51	23	45
Bermejo	26	5	−2	26	12	28
Brazil						
Itajai	8	64	−5	1	11	24
Uruguay	25	36	0	4	7	20
Jacuy	11	47	7	19	10	34
Ijui	19	24	−1	16	7	25
Ibicui	17	21	2	23	8	34
China						
Nen Jiang	16	12	−12	12	0	−12
Di'er Songhua Jiang	32	21	−5	17	−4	5
Songhua Jiang	13	4	−12	1	−9	−9
Danube						
Mures	−15	−8	−35	−12	−15	−50
Olt	−16	−10	−30	−16	−19	−13
Siret	−20	−7	6	−17	−20	−10
Tizsa	−10	−6	−29	−12	−15	−39
Sio	4	−2	−18	−2	−9	−34
Upper Danube	33	−16	12	9	−26	−5
South Western Danube	1	−5	−22	−8	−11	−40
United States						
Upper Missouri	−11	−6	4	−12	−11	2
Mid Missouri	−23	−2	24	−20	−7	24
Lower Missouri	−13	−3	43	−8	−6	33
Upper Mississippi	−31	−15	33	−33	−15	39
Mid Mississippi	−19	−9	35	6	−3	52
Ohio	−1	−8	−9	31	15	21

3.3. Changes in crop water demand

Projected changes in crop water demand vary from one study area to another, as well as between water regions within each study area (Table 4). Results depend on complex interactions of the effects of elevated atmospheric CO_2 on crop growth and water use, and temperature and precipitation changes as projected by the climate change scenarios. The changes vary by climate change scenario, decade, and crop. As with the runoff projections, results from the different climate change scenarios for crop water demand vary in sign and magnitude. Crop water demand in the Danube tends to decrease in most scenarios and regions, while projected water demand in Argentina and Brazil tends to increase. In the US, the GFDL and GISS scenarios primarily project declines in runoff, while the MPI scenario projects increases in runoff that average +21% for the 2020s and +28% for the 2050s. Changes in water demand in China are generally smaller (~+/−10%).

3.4. Supply and demand balance

WATBAL and WEAP results for the 2020s are shown in Table 5. The table shows the following quantities: modeled runoff from WATBAL; WEAP-estimated total water demand from industrial, municipal, and agricultural sectors; demand met (monthly average percentage of water demand met); reliability (percentage of years in which water demands are met); and demand-to-runoff ratio. The results for the optimistic and pessimistic futures for the GISS, MPI and GFDL scenarios provide the basis for the case study analysis in Section 3.5.

The last measure, demand-to-runoff ratio, is an indicator of the degree of economic development and its resulting impacts on the sustainability of aquatic and terrestrial ecosystems. As the water supply in a region

Table 5
WEAP regional water availability analysis for the 2020s

	Base	Optimistic				Pessimistic			
		W/O CC	GFDL	GISS	MPI	W/O CC	GFDL	GISS	MPI
Hungary and Romania									
Runoff ($10^9\,m^3$)	302	302	307	313	459	302	307	313	459
Water demand ($10^9\,m^3$)	28	21	25	26	27	29	28	29	29
Demand met (%)	97	98	98	97	98	96	97	96	98
Reliability (%)	83	88	85	83	91	81	81	81	88
Demand/runoff (%)	9	7	8	8	6	9	9	9	6
Argentina									
Runoff ($10^9\,m^3$)	121	121	109	129	110	121	109	129	110
Water demand ($10^9\,m^3$)									
Demand met (%)	97	97	97	98	98	97	97	98	97
Reliability (%)	81	81	78	82	79	77	74	78	75
Demand/runoff (%)	5	4	5	4	5	4	6	4	5
Brazil									
Runoff ($10^9\,m^3$)	239	239	337	230	249	239	337	230	249
Water demand ($10^9\,m^3$)	5	4	5	5	5	4	5	5	5
Demand met (%)	100	100	100	100	100	100	100	100	100
Reliability (%)	100	100	100	100	100	100	100	100	100
Demand/runoff (%)	2	2	1	2	2	1	1	2	2
China									
Runoff ($10^9\,m^3$)	67	67	59	74	73	67	59	74	73
Water demand ($10^9\,m^3$)	29	26	46	33	33	27	51	36	37
Demand met (%)	94	94	92	93	92	94	92	92	92
Reliability (%)	72	73	63	68	66	73	60	65	63
Demand/runoff (%)	44	39	77	44	45	41	85	49	50
United States									
Runoff ($10^9\,m^3$)	462	462	525	465	369	462	525	465	369
Water demand ($10^9\,m^3$)	174	115	114	116	124	122	139	141	150
Demand met (%)	98	99	100	100	93	99	100	100	93
Reliability (%)	94	97	99	99	86	96	99	99	86
Demand/runoff (%)	38	25	22	25	34	27	26	30	41

Note: Base climate = 50 years of SAMS data for each water region (USBR); w/o cc = without climate change.

becomes more developed, managed, and utilized, the cost per unit of further development increases at a nonlinear rate. Accessible, low-cost reservoir sites are no longer available, while the remaining sites tend to be remote and expensive to develop; they also tend to involve environmental damages or to require excessive costs to mitigate these impacts. The environment becomes further stressed as more water is stored in reservoirs and returned with added wastes. Four classes of stress can be defined relative to the demand-to-availability ratio: no stress [< 0.1], low stress [0.1–0.2], medium stress [0.2–0.4], and high stress [0.2–0.4] (Raskin et al., 1997).

3.5. Case studies

The international case studies are from regions that differ widely in climate, level of development and technology, and institutional and political structures, although all of the regions are relatively wet in current climate conditions. In all cases, the demand for water is met more than 90% of the time, even though the demand-to-runoff ratios vary considerably. This is due to the differing levels of regulated water, e.g., dams and reservoirs, in the different basins. In all cases, reliability increases when the demand-to-runoff ratio is low.

Argentina: Large-scale agriculture has been important in Argentina for well over a century: the country has long been an exporter of grain and meat. Institutionally, Argentina has been moving away from the heavily state-influenced economy of the post-World War II period. The study area includes two of the largest cities in Argentina after Buenos Aires: Cordoba and Rosario, and the region has substantial industrial activity. The climate ranges from semi-arid to temperate. The river systems in the region include tributaries that flow from the west to the Parana. There are large areas of wetlands and flatlands. Currently, Argentina has occasional problems in water supply for agriculture.

GCM projections for Argentina in the 2020s show little change in projected water supply; in the pessimistic case there is a slight decrease in system reliability under all GCM scenarios. Some tributaries may experience stress, but mainstream Parana sources are available to relieve this, providing suitable investments are made.

Brazil: The study area in Brazil, in the provinces of Santa Catarina and Rio Grande do Sul (bordered on the south by Uruguay), are the most southerly provinces of Brazil. The region encompasses a series of tropical humid basins draining eastward to the Atlantic and westward to the Uruguai River. These basins currently have abundant water supplies and agriculture in the region is primarily rainfed. Agriculture in the region is large-scale, with expanding areas of maize and soybean.

Under the climate change conditions projected for the next two decades, water supply for agriculture appears to be plentiful, even within the individual basins and even leaving aside mainstream Uruguai sources. However, one possible future outcome is increased flooding, which may well require investment in drainage facilities.

China: The study area of Jilin and Heilongjiang provinces lies in the northeastern region of China. Population is rapidly growing with internal immigration from other regions of China. The case study region is already heavily industrialized, including the Daqing oil fields. The Songhua River is the largest river within the region, draining north to the Amur (Heilongjiang). Part of the western drainage of the Songhua arises in the Inner Mongolian Autonomous Region. The area is bordered by the far eastern part of Russia. It has a cold continental climate that is, however, suitable for agriculture. The area has extensive freshwater wetlands. NE China is being developed as a center for mechanized and irrigated agriculture with larger field sizes than are often found in other parts of China. However, the water supply of the area is highly stressed under the current climate, with low reliability of water availability, and it is subject to substantial flooding. Irrigation efficiency is thus an important consideration in this region. Because of the closure of China to the West during much of the recent half century, data acquisition and specification of water management infrastructure are more difficult than in the other study areas.

Of the regions studied, China appears to suffer from the greatest lack of water availability for agriculture both now and in the coming two decades. Under all scenarios, there are decreases in system reliability due to increases in water demand, especially in the pessimistic cases. Both reliability of water supply and provision of water for ecosystem services are the lowest among the areas studied.

Hungary and Romania: Hungary lies entirely, and Romania almost entirely, within the Danube basin, which has played a crucial role throughout their national histories. The basin is generally temperate and with plentiful water supplies, although some water regions experience drought stress occasionally under current conditions. Significant flows arise from snowmelt in the upper basin.

For the 2020s, GCM results suggest that runoff will generally remain approximately the same as seen in current conditions or increase. The climate change scenario with increased runoff provides an increase in system reliability, while there are small decreases in reliability under the other two scenarios in the pessimistic case. While the basin as a whole has large amounts of water, some tributary areas are expected to be stressed, with consequent susceptibility to drought.

Environmental stresses are projected for the future both with and without climate change in the Danube region, but climate change causes shifts in the stresses within the region (Fig. 6). This has implications for

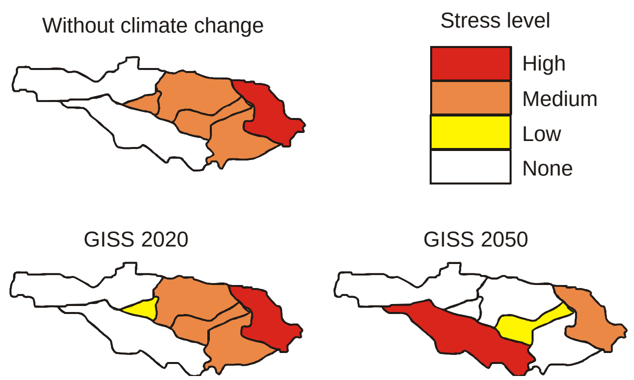

Fig. 6. Projected changes in environmental stresses in the Danube region for the future without climate change for the GISS climate change scenario in the 2020s and 2050s.

environmental management in the coming decades. These results integrate the combined impacts of climate change on water supply and water demand as well as the effects of population growth and economic development. The northwestern portions of the Danube Basin are projected to be less susceptible to environmental stress in the future, while the southwestern and eastern regions are projected to be stressed.

These are long-developed agricultural areas, still in transition from the agricultural collective system. Thus, there is great potential here for modern agricultural development through efficient application of fertilizer, herbicide and pesticide use, and better regional and on-farm water management. Hungary is among the most developed of the former Eastern Bloc nations, while Romania is further behind in the transition to a free-market economy and in the rebuilding of its institutions. In Romania, there is potential for significant expansion of irrigated agriculture. Here, revitalizing agriculture appears to be a particularly viable economic development strategy.

3.6. Additional climate change scenarios

The impacts of additional GCM climate change scenarios (HC and CCC) on runoff were calculated with WATBAL for China and the US in order to compare runoff generated with the original set of scenarios (Table 3) with more recent ones (Table 6). For the 2020s, runoff results from the Hadley Centre model are near the range of runoff projected using the first set of scenarios, while the Canadian Climate Centre model projected more extremes in runoff (wetter in the US Cornbelt and drier in China). For the CCC scenario in the US Cornbelt, the 2050s projections are much drier than those of the 2020s, compared to the HC scenario, which exhibits only small changes between the two time periods. The CCC scenario for 2050 results in large runoff reductions in 5 of the 6 water areas, while in the HC scenario 4 of the 6 basins show a slight-to-moderate increase in flow, and the remaining 2 areas show a slight decrease.

Table 6
WATBAL regional water supply (runoff) for base climate, 2020s and 2050s for the CCC and HC climate change scenarios

Country—Basin	Scenario runoff ($10^9\,m^3$)				
	Base	CCC 2020s	HC 2020s	CCC 2050s	HC 2050s
US—U. Missouri	39	77	38	55	40
US—M. Missouri	25	50	52	36	48
US—L. Missouri	23	10	21	6	15
US—U. Mississippi	49	71	50	42	51
US—M. Mississipi	99	162	105	55	97
US—Ohio	227	386	236	195	261
US	462	765	502	389	512
China—Nen Jiang	21.5	13.3	22.4	21.7	21.7
China—Di'er Songhua	23.3	16.2	29.9	22.7	22.7
China—Songhua Jian	22.2	13.8	23.4	22.6	22.6
China	67	43.3	75.7	67	67

Note: Base climate = 50 years of SAMS data for each water region (USBR).

For the case study area in Northeast China, the HC scenario results indicate that runoff in all the water regions is projected to remain either at or near current values in all cases, except for the Di'er Songhua Jiang in the 2020s where the runoff is 25% higher due to the higher precipitation shown in this GCM scenario. The CCC climate change scenario shows dramatic decreases in runoff for all water regions in Northeast China in the 2020s, including decreases as large as 33%, but in the 2050s, runoff is projected by the CCC to be near present-day values.

Results of WEAP modeling for China and the US with the additional scenarios are shown in Fig. 7. For China, there are dramatic reductions in system reliability for the CCC scenario and for two of the three basins under the HC scenario. The CCC results also show large differences in reliability between the 2020s and the 2050s. Results for the US show no impact on system reliability for 5 of the 6 water regions under both new GCM scenarios and for all time periods. In the Lower Missouri basin (where reliability is lower in the base climate), the HC scenario exhibits significant improvement, while the CCC scenario causes reliability to plummet.

The decadal variations in water availability shown across all the GCM scenarios indicate that the effects of global warming on regional water regimes are likely to be non-monotonic. A general physical reason for these results is that the different elements of the global climate system do not change at the same rates. It is also true that the ways in which the GCMs currently in use capture these differential changes are partly responsible

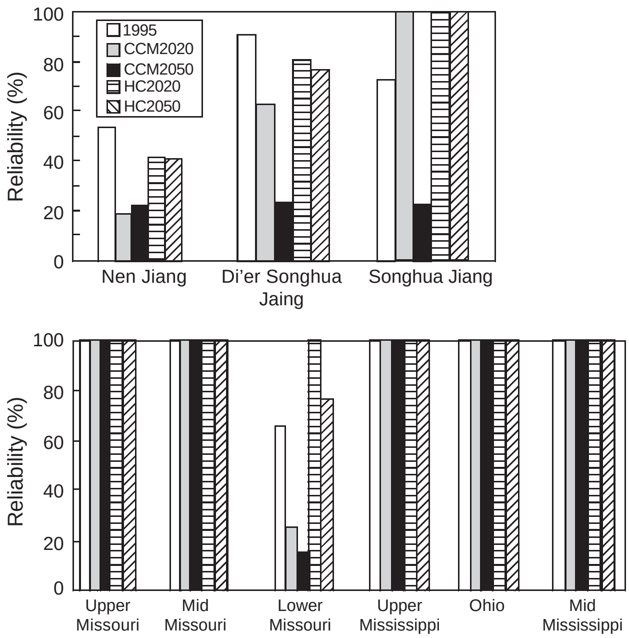

Fig. 7. Projected changes in water reliability for the CCC and HC climate change scenarios.

for the particular results shown; this is an area that requires further investigation into physical processes and model specification.

3.7. Water resources adaptation

Technology: In the core set of modeling simulations, results indicated that reliability of water systems in the case study regions would not be dramatically reduced by climate change. Because the core set of simulations included both projected climate changes and estimated improvements in irrigation, industrial, and municipal and domestic water-use efficiency, we tested the sensitivity of the results to improvements in technology related to irrigation efficiencies at medium and high levels (Table 7).

In China, the impact of improved technology is seen in the reductions of both water demand and demand-to-runoff ratio (environmental stress), each of which drop by about 20% under highly efficient irrigation conditions. Improved irrigation efficiency and consequent reduction in demand have a much smaller effect (only a 4% increase) on water system reliability, because return flows are stored as groundwater and are available for use in the next timestep. In contrast to the relatively low sensitivity to technology in regard to system reliability in China, the Lower Missouri in the US responds to improved irrigation efficiency not only by reducing demand by 25% and lessening environmental stress by 33%, but also by improving system reliability by 14%. Because the region is primarily agricultural, demand for irrigation exceeds industrial and municipal demands.

Table 7
Sensitivity of water availability to medium and high levels of irrigation efficiency for the optimistic population and economic scenario for the 2020s with current climate and 1995 irrigation area

	1995	Mid level	High level
China			
Irrigation efficiency (%)	45	50	55
Runoff ($10^9\,m^3$)	67	67	67
Demand ($10^9\,m^3$)	31	27	25
Demand met (%)	94	95	95
Reliability (%)	72	74	75
Demand/runoff (%)	47	41	38
US Lower Missouri[a]			
Irrigation efficiency (%)	50	60	65
Runoff ($10^9\,m^3$)	23	23	23
Demand ($10^9\,m^3$)	31	26	23
Demand met (%)	89	93	96
Reliability (%)	66	73	82
Demand/runoff (%)	133	113	100

[a]Strzepek et al. (1999).

Thus, sensitivity to technology assumptions, while variable, is likely to be important in all the study areas. The major improvements postulated under the high technology scenario do contribute to the significant impact. An implication of these results is that irrigation and drainage technology are likely to become even more important in the coming decades than they are now.

Irrigated area: The core set of simulations assumed that land under irrigation remained at 1995 levels, except in the case of the US. We tested two levels of expansion—Full and Mid (half of full). The Full level includes an assumption of world increase in demand for animal protein equivalent to the forecast increases in population and an additional increase equivalent to a percentage of forecast world GDP increase. The scenarios were developed for all study areas except the US, where we assume that irrigated acreage is likely to remain constant over the next two decades. Table 8 presents a summary of the results incorporating both expansion of irrigation area and the climate changes projected by the MPI, GFDL, and GISS GCMs for the 2020s.

The results imply that the Brazil case study area can readily accommodate an expansion of irrigated land, while the other three study areas—Hungary and Romania, Argentina, and China—would suffer decreases in system reliability up to 18% if irrigation areas were to be expanded. In the Argentine tributaries studied, however, mainstream sources could be used to offset sub-basin shortages. These results suggest that under the projections of climate change used in this study, Brazil has the most potential for expansion of irrigation.

Table 8
Sensitivity of water availability for the 2020s to irrigation area expansion for the optimistic population and economic scenario

	No change			Mid			Full		
	GFDL	GISS	MPI	GFDL	GISS	MPI	GFDL	GISS	MPI
Argentina									
Runoff ($10^9 m^3$)									
Water demand ($10^9 m^3$)	6	6	5	10	9	8	14	12	11
Demand met (%)	97	97	97	96	96	96	95	95	95
Reliability (%)	78	81	82	71	74	76	65	70	72
Demand/runoff (%)	5	4	4	8	7	6	11	9	8
Brazil									
Runoff ($10^9 m^3$)									
Water demand ($10^9 m^3$)	5	5	5	8	8	7	11	11	9
Demand met (%)	100	100	100	100	100	100	100	100	100
Reliability (%)	100	100	100	100	100	100	99	97	99
Demand/runoff (%)	2	3	2	2	4	3	3	6	4
China									
Runoff ($10^9 m^3$)									
Water demand ($10^9 m^3$)	51	36	37	60	57	48	84	80	68
Demand met (%)	92	92	92	83	83	87	78	78	82
Reliability (%)	60	65	63	56	56	60	53	54	56
Demand/runoff (%)	85	49	50	92	80	49	130	113	69
Hungary and Romania									
Runoff ($10^9 m^3$)									
Water demand ($10^9 m^3$)	26	27	26	32	33	32	38	39	37
Demand met (%)	98	97	98	96	96	97	94	94	96
Reliability (%)	85	84	91	78	78	85	73	74	81
Demand/runoff (%)	9	9	7	11	11	8	13	13	10

No change—current irrigated acreage; Full—expansion of irrigated acreage based on increases in population, GDP, and demand for animal protein; Mid—half of full.

3.8. Agricultural adaptation

Genetic resources: Two cultivars were tested with contrasting characteristics related to adaptation to warmer temperatures (Fig. 8). One (#14) has lower sensitivity to photoperiod, allowing it to be planted at different times of the year; the other (#10) has higher yield potential under warmer conditions. Cultivar #10 was able to compensate for the yield reductions caused by the climate change scenarios, while cultivar #14 was not. On the other hand, cultivar #14 was less sensitive to planting date, and offers the potential for yield stability under a range of management conditions. From a water availability viewpoint, however, both cultivars require greater irrigation water, even under current climate conditions (Fig. 9). This suggests that both yield and water use should be taken into consideration when planning climate change adaptations for agriculture.

4. Conclusions

The modeling approach presented here provides a meaningful framework for analysis of the status of major agricultural regions in the world under climate change. Overall, the project results suggest that, at least for the relatively wet areas studied, there will be sufficient water for agriculture in the coming decades. The WEAP model results imply that increased water demands from population, industry and agriculture, and potential supply changes from global climate change can be matched as long as improvements in crop, irrigation and drainage technology, better water management (such as the increasing use of water markets and demand control measures) and adequate investments are achieved.

The signal of climate change effects on regional hydrological regimes is projected to be small for the decades and areas studied, but some models give conflicting results. Some changes in extreme events are likely to occur in some of the regions, but no major changes in mean climate in terms of its provision of water for agriculture are foreseen. However, some changes in seasonality of water supply and demand may be manifested. Climate model projections indicate progressively larger changes in the 2050s and beyond. The use of the additional available GCM scenarios reinforces the fundamental uncertainty of climate

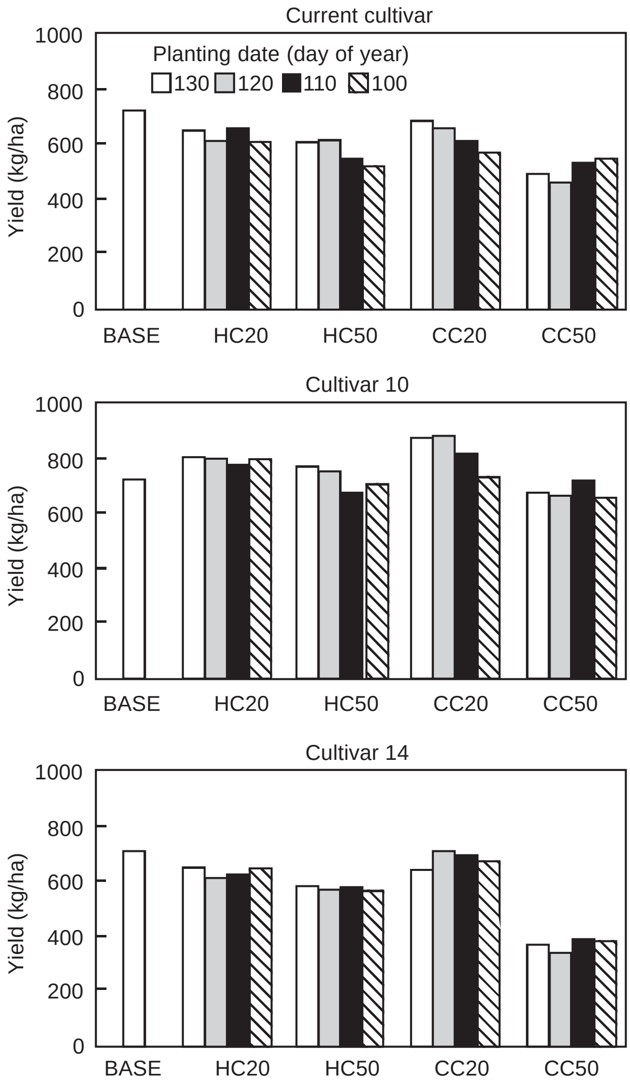

Fig. 8. Simulated yield of current and alternative maize cultivars and planting dates in Grand Island, Nebraska (US) under current climate and the CC and HC climate change scenarios.

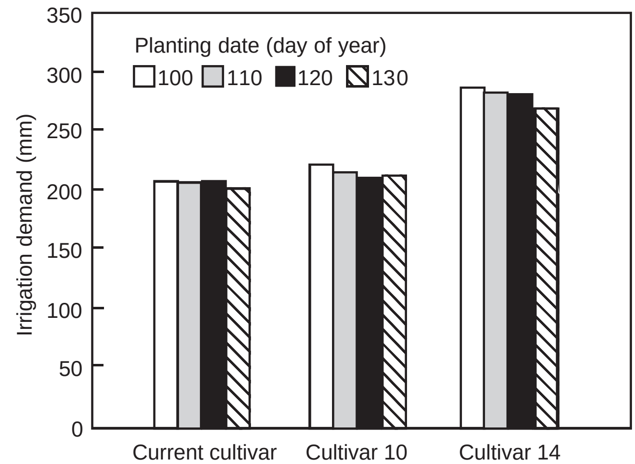

Fig. 9. Irrigation demand for current and alternative maize cultivars and planting dates under current climate conditions in Grand Island, Nebraska (US).

change as it relates especially to precipitation, and enhances the importance of continued technological advance, institutional adaptation, and investment in the water and agriculture sectors.

Future differences are found among the study regions, with NE China projected to be the most stressed in terms of water supply for agriculture and Brazil maintaining the most abundant supplies. The US Cornbelt indicates ample supplies in the projections, while in Hungary and Romania and Argentina, stress is projected to occur in some water regions and some scenarios by 2020. Argentina may need to rely increasingly on the main flow of the Parana, if tributary water supplies become limited. Climate change scenarios suggest that Brazil may more readily accommodate an expansion of irrigated land, while the other three study areas—Hungary and Romania, Argentina, and China—would suffer decreases in system reliability if irrigation areas were to be expanded.

When climate models project increased precipitation and variability, more investments in drainage may be indicated since flooding of agricultural land is likely to occur more frequently. Both because of climate change and because of increased demands, the intra-seasonal timing of water on crops will require increased attention. Irrigation and drainage technology are likely to become even more important. The importance of seasonality is indicated, and this suggests continued flexibility in the development of new varieties.

Future directions for this research include the extension of the analysis to other regions, especially in less water-rich areas that are vulnerable both at present and in the future, in order to gain insight into the maximum effects of climate change on agriculture; and the use of more recent socioeconomic scenarios and more recent GCMs. Further methodological work would include use of filtering techniques to separate the effects of climate variability from climate change, assessment of costs for technological change, investment, and water quality control; evaluation of area-based PET values, versus more geographically targeted values; and detailed modeling of water quality that requires a spatial scale of analysis smaller than the current approach.

Increased water demands from population, industry and agriculture must be accommodated by timely improvements in water management, institutions, and crop, irrigation and drainage technology. These improvements will require substantial resources and expertise. For the relatively water-rich areas studied, there appear to be possibilities for the adaptation of efficient technology, control of demand, changing institutions and other adaptive mechanisms that will allow for continued agricultural productivity in the coming decades under changing climate conditions. This suggests, however, that these intensely managed areas will likely become even more so, while those that are already relatively dry may be faced with much more stringent obstacles to continued and expanded agricultural productivity under climate change.

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